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DENSITY IRREGULARITIES IN THE PLASMASPHERE BOUNDARY LAYER: CLUSTER OBSERVATIONS IN THE DUSK SECTOR

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ABSTRACT

We present observations of plasma density structures crossed by the CLUSTER spacecraft constellation near orbit perigee, with the spacecraft located in the vicinity of the plasmapause boundary. Although the constellation is not arranged as a perfect tetrahedron, the four point measurements reveal interesting properties of density structures, unknown before the 4-points in-situ observations from the CLUSTER mission. The set of plasma density profiles shown are derived from the EFW and WHISPER instruments observations in the dusk sector of the plasmasphere region. They yield new insights into: (i) comparative along and cross-field dimensions, and (ii) the dynamics of small-scale structures. They illustrate the great opportunity offered by the CLUSTER mission to resolve new challenges in magnetospheric physics, including a clearer understanding of the physics involved in the dynamics of the plasmasphere and the formation of its outer boundary: the plasmapause.

INTRODUCTION

One of the main objectives of the multi-spacecraft CLUSTER mission is the study of small-scale plasma structures. The grounds for using four measurement points is to overcome the limitations of a single spacecraft, or even of a pair, in resolving the spatio-temporal evolution of plasma structures; indeed such information is crucial for understanding the underlying physical mechanisms, involved in the formation of new plasmapause density gradients. We present here case studies of density irregularities observed by CLUSTER in the plasmapause region. We show how a comparison of the four measured density profiles can improve our *in-situ* perception and knowledge of this key magnetospheric region.

Recognizing that a four spacecraft formation is not able to fully resolve the evolution of a plasma structure in the general case, we follow here two main approaches. The first one considers the simple problem of a rigid planar structure drifting at constant velocity during the time interval when it is crossed successively by the four spacecraft. Under such circumstances, the speed V along boundary normal, and corresponding direction **n**, can be determined from the so called timing analysis method. The method relies on the equation $\mathbf{r}_n \cdot \mathbf{n} = V\, t_n$, where $\mathbf{r}_n$ and t_n are the differential positions and times of crossing by three spacecraft relative to position and time of crossing by the fourth spacecraft chosen as reference. This method has proven to be successful in a number of studies carried on by CLUSTER (see for instance Dunlop et al., 2002). The second approach compares simply the shape of the four density profiles and identifies similar features in those profiles as signature of a structure coherent in time and/or space. This is facilitated by plotting density variations as a function of the L parameter. Relative spatio-temporal positions of identified features can further be used to derive useful characteristic dimensions.

The paper is divided in two main parts. The first part presents the **general context**: density measurements, orbital properties, general features observed in the Plasmasphere Boundary Layer (PBL, Carpenter, 2004). The second part presents **detailed observations** of two density structures, and some discussions about the physical processes implied.

GENERAL CONTEXT

Measurement techniques

The density observations discussed in this paper are obtained by combining two instruments of CLUSTER: EFW (Gustafsson et al., 1997) and WHISPER (Décréau et al., 1997). Spacecraft potential values V_{SC} derived at a high time resolution by EFW follow the electron density N_e variations in a given plasma regime (Laakso and Pedersen, 1998). They can be calibrated by WHISPER measurements (Moullard *et al.*, 2002). Plasma frequency variations discussed in this paper are obtained from measured values of Vsc and the empirical parametric relationship: $N_e = A * V_{SC}^{-B}$. The constant A and B are obtained by fitting data subsets of Vsc measurements and of N_e values derived by the WHISPER sounder at a lower time resolution (Trotignon *et al.,* 2001).

Orbitography

CLUSTER travels on a polar orbit of large eccentricity (4 and 19.5 Earth radii respectively at perigee and apogee). During main manoeuvres (activated at least once a year), the spacecraft orbits are adjusted in order for the constellation to form a perfect tetrahedron of prescribed dimension usually in the cusp or close to the magnetopause.

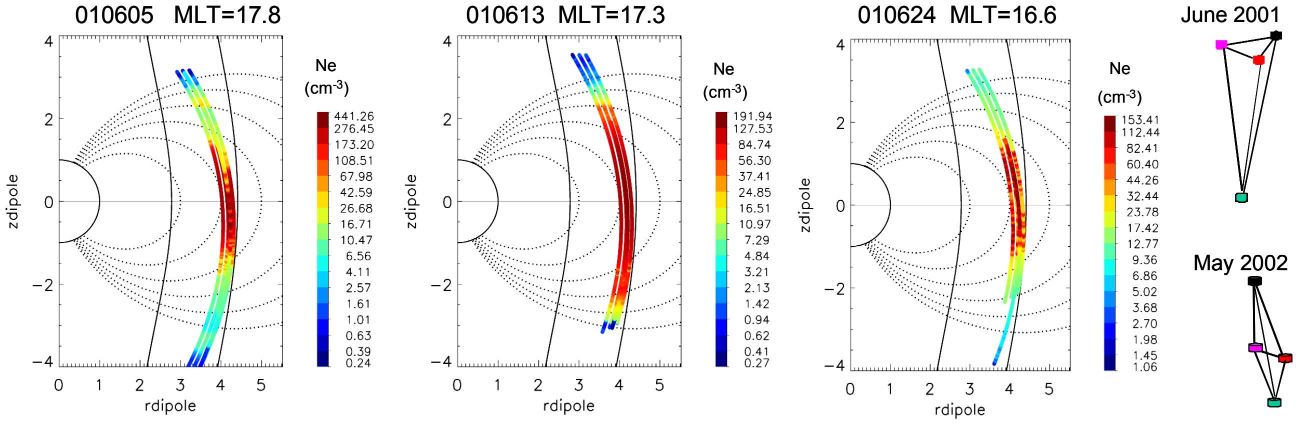

Fig.1. Colour coded density values measured at three perigee passes in the dusk sector, plotted along the spacecraft orbits in the SM coordinate system. C4 travels at the lowest altitudes, C1 at the highest ones. At intermediate altitudes, the track of C3 hides that of C2, taken about 45 minutes earlier. Dotted curves are dipole field lines (from L=3 to L=8). Solid curves are cuts of Roche limit surfaces. Constellation configurations close to perigee are sketched on the right (C1 in black, C2 in red, C3 in green and C4 in purple), respectively for the June 2001 epoch and for the May 2002 epoch (event of figure 5).

This results in an elongated constellation shape at perigee, where the plasmasphere region is encountered. In figure 1 each panel displays, for a given perigee pass, colour coded density values measured at successive spacecraft positions along the four orbit tracks. The orbit tracks are plotted in a meridian plane of the solar magnetic (SM) coordinate system (Russell, 1971), where the abscissa r measures the distance of the spacecraft to the dipole axis and the ordinate z measures the distance of the spacecraft to the magnetic dipole equator. Such a presentation erases the local time differences at the various spacecraft positions, and only three orbit tracks appear as being distinct. The shape of Cluster configuration is sketched on the right of the figure, respectively top right for large average separation (June 2001) and bottom right for small separation (May 2002). In both cases, the largest separation (~ 10000 km in June 2001, ~ 300 km in May 2002) is aligned roughly along the orbit, tangent to the magnetic field direction at the equator. Across the orbit, the average separation is ~ 2000 km in June 2001, ~ 60 km in May 2002. The shape is less regular at large separation, three spacecraft, C1, C2 and C4, being grouped as a trio, than at small separation.

Dipole field lines are plotted from L=3 to 8 (dotted lines), where the McIlwain parameter L (McIlwain, 1961) identifies a surface of cylindrical symmetry with respect to the dipole axis. Real field line orientations measured onboard by the FGM instrument (Balogh et al., 1997) deviate from this representation, which nevertheless guides the eye to recognize global features. It takes about 1 hour 40 minutes for a spacecraft to travel from South to North between the two orbit positions located at L=6. MLT values at perigee are listed at the top of each orbit plot. They are decreasing from South to North, of about 1.8 hours between the two orbit positions located at L=6.

General topology

Several interesting features appear clearly on figure 1, illustrating a general behaviour:

1) the major density structures are globally field aligned. This is particularly true for the rather sharp density gradients typical of the plasmapause knee ('yellow' density levels in the 13th June 2001 plots). It is also the case for density features separated from the main plasmasphere body as viewed on an orbit cut, which does not mean that the feature is necessarily detached (see example at L= 6, in the 5th June 2001 plot, northern hemisphere),
2) a large number of density irregularities (10 to 200 cm^{-3} N_e levels, typical density variations observed at plasmapause) are observed on some orbits (5th and 24th June 2001). The region encompassing those irregularities appears as rather large (entire orbit segment below L ~ 5), roughly centred on the magnetic equator. This region has recently been called the Plasmasphere Boundary Layer (Carpenter, 2004).

The solid lines highlight two positions of the cylindrically symmetric Roche limit surface, or Zero Parallel Force (ZPF) surface if the angular velocity of the plasma would be 3 times larger than the corotation velocity (inner curve) and 1.5 times the corotation velocity (outer curve). According to the theory outlined by Lemaire (1999, 2001) the part of the plasmasphere outside this limit is convectively unstable, leading to the formation of quasi-interchange modes (see Ferrière et al., 2001) with a non-zero component of the k-vector parallel to the magnetic field lines. This produces small-scale density irregularities and leads to plasmapause formation via erosion in the post-midnight MLT sector, where the plasma angular velocity is the largest and the ZPF surface closest to Earth. André (2004) has calculated that the characteristic time for this type of instability is of the order of 10 minutes.

It happens that the Cluster orbit below L ~ 5 is roughly aligned with a Roche limit surface, such that a large orbit segment will encounter similar unstable conditions if the surface happens to meet the orbit position, i.e. at plasma angular velocities about twice that of co-rotation. The presence of irregularities along large orbit segments is compatible with the hydrodynamic instability (HI) theory proposed by Lemaire. Let's hope that future studies will enable us: (i) to follow the formation of irregularities in the post-midnight sector and during magnetic substorms, where and when they are supposed to form; (ii) to identify how these density irregularities are convected away from the unperturbed co-rotating inner part of the plasmasphere, to be found later in the dusk sector.

DETAILED OBSERVATIONS

Observations of the plasmapause region when spacecraft are widely separated

Large separations are linked to large time intervals between spacecraft when crossing the same region of space. In June 2001, three spacecraft (C1, C2, C4) were within 2000 km of each other (sketch of Figure 1); C3 was significantly farther (at a distance of about 10 000 km from the trio). The perigee is then at 17.3 MLT.

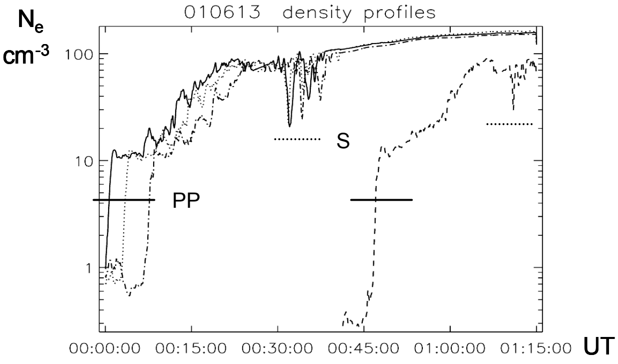

Fig.2. Compared density time profiles obtained on spacecraft C1 (solid line), C2 (dotted line), C3 (dashed line) and C4 (dash-dotted line), at the inbound leg of the 13 June 2001 pass. The analysed features, PP and S, are pointed.

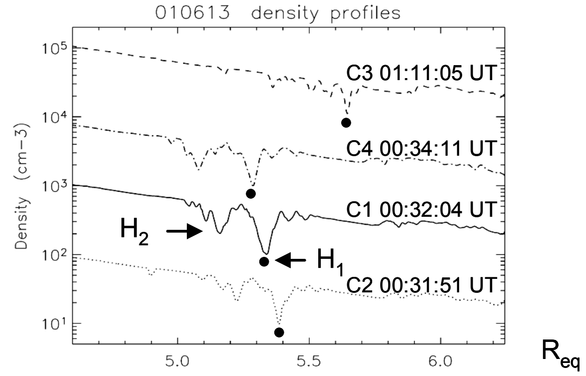

Fig.3. Details of the structure S: density versus R_{eq} parameter. Density values have been multiplied by 10 for C1, 100 for C4 and 1000 for C3. Time runs from right to left. UT values are given at pointed H_1 dips.

Such an elongated configuration can be used for testing the stability of large scale boundaries. Using the timing analysis method described in the introduction, we have analyzed the motion of the plasmapause (PP) crossed around 00:05 UT by the C124 trio and 40 minutes later by C3 (as shown in Figure 2). This requires three conditions to be met: planarity, rigidity and velocity constancy. The four crossing points form a tetrahedron of reasonable characteristics, leading to a satisfying precision (~ 5%) both on orientation and magnitude of drift velocity. This tetrahedron is inscribed within a sphere of ~ 1000 km radius, such that the requirement of planarity of the travelling boundary needs to be satisfied only at that scale. The position of the crossings are shown in figure 1 (middle panel) by the yellow region at L ~ 8, southern hemisphere. There, the magnetic shell curvature radius is large enough (about 5 R_E) for planarity to be satisfied locally. Concerning the rigidity, we note a striking similarity between the four density profiles displayed in Figure 2 (discarding small scale features). The thickness of the overall boundary layer and density distribution within, which are not varying significantly from one pass to the other, can qualify both as 'rigid' and travelling at a roughly constant velocity. The timing analysis indicates that the plasmapause velocity is low: 0.33 km s^{-1} in the GSE system (the total displacement over the large time interval studied is only 910 km, ~ 0.15 R_E). The respective components of the boundary unit normal are 0.78, 0.26 and 0.56. This vector is not oriented parallel to the local meridian plane (the X component is not small), as could be expected from an axi-symmetric plasmapause. Considering that the boundary is encountered at a large L value (L = 8) in the dusk sector, the likely explanation is that the plasmasphere expands in a bulge along the Y axis. The bulge is crossed by Cluster on its night-side flank, aligned with a magnetic shell oriented roughly along the 18 MLT meridian plane. We have tested the likeness of our interpretation and assumptions against independent information: the DC magnetic field vectors measured by the FGM instrument at the four crossing points. The four vectors have the same orientation within ± 2° (confirming planarity). They are all perpendicular to the estimated boundary normal (within ± 2°), confirming the view of a plasmapause locally aligned with a magnetic shell.

After 00:30 UT, small scale structures (S) with large density indentations show up in the electron density versus time profiles of Figure 2 (density scales are shifted). In order to facilitate the comparison of the four profiles, we can plot the N_e values measured at various positions as a function of the L parameter. Such an approach is directly relevant to *in-situ* observations when they are obtained by quasi equatorial missions, like ISEE 1. In the case of Cluster, we make use of a magnetic field model, combining IGRF95 and Tsyganenko-96 (Tsyganenko and Stern, 1996). We follow the magnetic field line provided by the model from the spacecraft position to the equator (identified by a minimal magnetic field strength value), using the Unilib library (see reference list). The geocentric distance of this equatorial point, which we call R_{eq} and which we express in Earth radii, plays the same role as the L value. As this paper deals mainly with small structures, we ignore the density variation with altitude in a magnetic tube of constant flux. All density values presented are raw *in-situ* measurements.

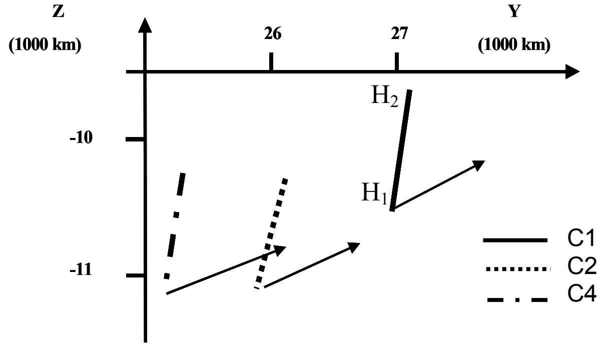

Fig. 4. Case event of 13 June 2001. Position of the density structure H_1H_2 *(line style as in Figure 2) in a meridian plane of the SM coordinate system. The arrows indicate the respective magnitudes (350 nT for C1) and orientation of the measured magnetic field vectors.*

The details of the indentation crossed around 00:30 UT by the C1, C2, C4 trio, are displayed in Figure 3. They point out the same density signature, referred to below as H_1H_2: a pair of density holes separated by roughly 0.2 R_E along the R_{eq} parameter. In Figure 3, time runs from right to left and from bottom to up: C2 crosses the structure the first, C1 13 s later (H_1, the first encountered density hole, is chosen as marker), C4 127 s after that, and finally C3, roughly 40 minute after the trio. The orbit elements crossed by C1, C2 and C4 between the density holes H_1H_2 are located in almost the same meridian plane of the SM coordinate system (differences in longitude are less than one degree), which happens to be close to the YZ plane. In figure 4, those elements are plotted as line segments of the YZ plane. The three DC magnetic field vectors measured by the FGM instrument, plotted at the H_1 markers, are quasi parallel to this plane (at an angle below 3°). In this particular configuration, figure 4 shows that the three spacecraft, which are less than 350 km apart in the third dimension (along the X axis) are roughly aligned along a direction roughly parallel to the magnetic field direction. They recognize the same cross-field structure, within a short time interval.

We can now discuss the dimension of the double indentation structure. In the plane of figure 4 (YZ plane of the SM coordinate system), its overall size along the field direction is 2000 km or more, whereas the distance between the field lines respectively along H_1 holes and H_2 holes is about 800 km. The field line distance of smaller irregularities is below 100 km. In the third dimension – in longitude – we can only state that the structure is larger than the maximal spacecraft separation, i.e. about 350 km.

Another interesting piece of information derived from the multipoint measurements is the time life of the well defined density holes observed. A detailed inter-comparison of the three similar density profiles show actually slight differences between them, indicating either that there are differences over even smaller dimensions, or that the structure has evolved in time, over less than one minute time interval. Note that the profile measured by C3 is different, displaying shallower indentations (see figure 3). This could be a temporal effect, due to refilling (both magnetic feet are illuminated at ionospheric altitude), or to cross-field interchange motion. Alternatively, it could be a longitude effect (C2, C4, C1 and C3 are placed at increasing respective longitudes, within one degree total).

Observations of the plasmapause region when the spacecraft are close to each other

For a duration of about 4 months in 2002, the CLUSTER configuration has been adjusted to small separations, while the perigee was located in the midnight to dusk local time sector. Preliminary analysis confirms here also the presence of frequent small scale density irregularities in the vicinity of the plasmapause and inside the plasmasphere (Darrouzet et al., 2004); some of them can clearly be identified as the same entities on all four density profiles. We can in such cases apply the timing analysis, as done above.

Figure 5 displays detailed electron density profiles as a function of R_{eq} at the plasmapause discontinuity observed the 9th of May 2002 on the inbound leg near L = 6, around 19 MLT. There, the orbit track and the magnetic field lines make an angle of about 60°, hence successive field lines at decreasing R_{eq} are crossed rapidly: 1 R_E range in about 10 minutes. The four profiles show density values fluctuating between two smooth levels reached respectively in the high and low R_{eq} range, a typical situation in the outer plasmasphere region (as illustrated in Lemaire and Gringauz, 1998, chapter 2).

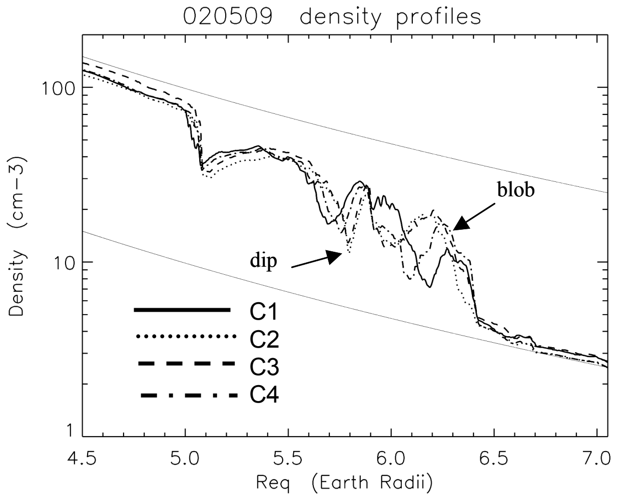

Fig. 5. Details of the electron density profiles versus R_{eq} parameter measured on 9th May 2002. Line code as in figure 2. The two thin lines are R_{eq}^{-4} profiles fitting observations respectively at low and high R_{eq} values. Arrows point to structures discussed in text.

These density fluctuations are well correlated, except near the foot of the plasmapause region ($R_{eq} \sim 6$), where it is clear that the four spacecraft do not sweep through a stagnant rigid 1D structure, like that detected below Req = 5.8. Various explanations can be proposed and considered: this can be a density structure of complex 3D shape which is standing still, or else a 1D double peak which varies in shape with time, or even more elaborated behaviours that will have to be examined in more comprehensive studies.

Focusing on the plasma blob of higher density observed between $R_{eq} = 6.0$ and $R_{eq} = 6.5$ R_E, we have conducted an analysis in the SM coordinate system (not to fully describe in this short paper). The exercise indicates that either the blob moves rapidly (at about 5 km s^{-1}) from a higher to a lower L shell, or that a discontinuity surface almost parallel to a local meridian plane separates C1 and C4 on one hand (earlier local times), from C2 and C3 on the other hand (later local times). This thin layer would be ~ 20 km wide. Across this thin layer, a rigid 3D blob could change position in L shell.

We have analysed the motion of the density dip observed at $R_{eq} = 5.7$ to 5.8 via timing analysis. In this case of a small constellation (largest separation of 350 km at traversal points in the moving plane), the assumption of a planar boundary seems justified. The exercise yields velocity components of respectively -2, 0.7, 0.5 km s^{-1} in the GSE co-ordinate system, indicating that co-rotation (~ 2 km s^{-1} at this position) is the major mechanism involved in the plasma motion. On the other hand, the local orientation of magnetic field is measured at an angle of ~ 30° with the boundary. If the conditions for applying timing analysis are met, part of the motion is parallel to field line. This opens the possibility of hydrodynamic instability (HI) with a parallel component of centrifugal force. The plasma interchange velocity value according to the HI model can be evaluated from the formula listed in Lemaire and Gringauz, 1998, p. 263. For the density irregularities shown in Figure 5 above Req = 5.5 (dip and blob with $\Delta n \sim 50$ cm^{-3}) it amounts to a value of about 0.2 km s^{-1}. If interchange is indeed at work, the corresponding motion of irregularities is too slow to be distinguished from co-rotation in this case, and we cannot conclude.

SUMMARY AND DISCUSSION

The configuration of CLUSTER orbits allows the four platforms to cross the outer region of the plasmapause, and has revealed large and small-scale patchiness of the plasma distribution in this transition region. The small separation (from 100 km up to 12 000 km) between the four spacecraft, combined with the very high time resolution (less than 3 s) of the WHISPER and EFW observations, offer unprecedented opportunities to study in greatest details the small-scale irregularities in the narrow region of the plasmapause boundary layer.

In this study, it has been shown that the plasma irregularities observed at the plasmasphere boundary have dimensions along magnetic field larger than 2000 km (at least in the case event analysed), cross-field dimensions ranging from less than 20 km to more than 350 km, and a wide range of lifetimes (from 10 seconds to several tens of minutes). Drift velocities have been derived from timing analysis, demonstrating – if simple assumptions are met – the slow motion of both a small and a large-scale density discontinuity. The results presented above constitute a first step toward further studies of plasma irregularities at the plasmapause boundary layer. In particular toward testing if plasmapause density gradients are forming due to plasma interchange instability (Lemaire, 1999, 2001).

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